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Development of a Polycyclic Aromatic Hydrocarbons (PAHs) emission inventory in Korea

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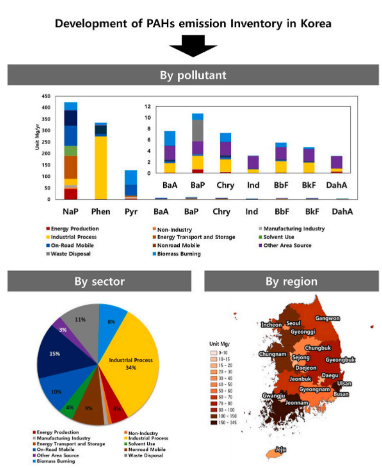
HIGHLIGHTS

- An emission inventory of 16 PAHs, including 7 carcinogenic PAHs, was developed for Korea using the latest data.
- Regional and sector-based emission estimation became possible.
- The total annual emission of 16 PAHs in Korea in 2017 was 1259.7 Mg, with 7 PAHs contributing 41.77 Mg.
- The Industrial processes was the main source of 16 PAHs, while wildfires dominated emissions of the 7 PAHs.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, an emission inventory of 16 PAHs, including 7 carcinogenic PAHs, was developed using the latest data for Korea. The study incorporated emission sources that had been omitted in previous studies. PAHs emissions were estimated by region (at city, county, and district levels) and sector to enable a more precise identification of the emission status in Korea. The total annual emission of 16 PAHs in Korea in 2017 was 1259.7 Mg, with 7 PAHs contributing 41.77 Mg. The major sector of the emissions of the 16 PAHs was *industrial process* (33.5 %). For the 7 PAHs, *other area source* was the major emission sector (38.8 %), mainly due to wildfires. In terms of regional aspects, regions with high Industrial Process activities such as ULSAN, JEONNAM,

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CHUNGNAM, along with GYEONGGI, a major hub for Korean Energy Transport and Storage, showed the highest emissions. The developed emission inventory was intercompared with other inventories, ensuring the appropriate application of emission factors for each emission sector. Especially, it was found that the Korean PAH emissions reported in EDGARv6.0 were 1.9–5.1 times different from those estimated in this study, depending on the pollutant. It was discovered that the emission factors in the *residential sector* in EDGARv6.0 may differ from the actual emission characteristics in Korea. The PAHs emission inventory developed in this study is anticipated to be used for the establishment and regulation of PAHs policies in Korea. Furthermore, the research results are expected to be essential reference material for refining the emission inventory of PAHs for Korea, which is used in atmospheric transport modeling.

1. Introduction

Air pollutants can be classified into Criteria Air Pollutants (CAPs) or Hazardous Air Pollutants (HAPs). CAPs consist of six major pollutants regulated under the National Ambient Air Quality Standards (NAAQS), owing to their widespread impact on public health and the environment. In contrast, HAPs comprise 187 toxic substances that can cause serious health effects even at low concentrations and are primarily regulated through source-specific emission standards (US EPA, 2015). HAPs are recognized for their carcinogenic and other harmful effects on human health (MOE, 2016; US EPA, 2015). Among HAPs, Polycyclic Aromatic Hydrocarbons (PAHs) stand out as particularly harmful due to their toxicity, persistence, bio-accumulative nature, and capability of long-distance transport (Ravindra et al., 2008; KoreaLicia and Adolfo, 1994). PAHs, which consist of two or more benzene rings, are primarily produced through the incomplete combustion or high-temperature pyrolysis of organic materials containing carbon and hydrogen from various emission sources. PAHs with high molecular weight (e.g., benzo(a)pyrene) exhibit low solubility in water, allowing them to persist in environmental habitats like soil and waterways, consequently posing significant toxicity to humans and animals.

Understanding the emission levels and characteristics of various PAH types from diverse sources is essential for the effective management and regulation of PAH emissions. A well-developed PAHs emission inventory will significantly aid in this understanding. Numerous studies have compiled PAHs emission inventories on a global scale. Examples include the Emission Database for Global Atmospheric Research (EDGAR) of the European Economic Area (EEA), as well as studies by Huizhong et al. (2013) and Yanxu and Shu. (2009). Additionally, Inomata et al. (2012) developed an emission inventory for nine particle-phase PAHs in the Northeast Asian region, including Korea. These studies enable cross-country comparisons but lack detailed data for non-major countries and have relatively lower accuracy for certain sources. As a result, they may be inadequate for providing detailed insights at national or regional levels. To address these limitations, researchers have conducted various studies on PAHs emissions inventories for each country. For instance, Yang and Chen (2004) developed an emission inventory for 21 PAHs at seven sites in a suburban area in Taiwan, and the US Environmental Protection Agency (EPA) developed the NEI for the United States, which provides emissions data not only for criteria pollutants and their precursors, but also for hazardous air pollutants—including 17 PAHs.

In Korea, there is significant concern about the harmful effects of PAHs, leading to their designation as specific air pollutants for management. PAH concentrations have been monitored in real-time through the air pollutant observation network in Korea, and the emissions of PAHs from air pollution emission facilities are regulated according to the "2020 Standards for Permissible Air Pollutant Emissions" (MOE, 2019). However, these regulations are limited to the most toxic compound, benzo(a)pyrene, and the basis for regulatory standards is not clear. It has been pointed out that there is insufficient information regarding precise emissions and associated risks of PAHs. Consequently, it is imperative to understand the exact status of PAH emissions. Although a national-scale study on developing PAH emission inventories in Korea has been conducted by Cho et al. (2000), the lack of basic statistical data makes it difficult to estimate emissions accurately. Furthermore, since the data are based on 1995, updates are necessary. Therefore, in this study, the PAH emission inventory for Korea was developed to accurately understand the recent emission status of PAHs.

The differences between the Korea PAHs emission inventory developed in previous studies and our study are as follows: Firstly, in this study, PAHs emissions were estimated based on the most recent data available, the Clean Air Policy Support System (CAPSS, NAIR 2020). As CAPSS is specifically designed to reflect Korea's domestic emission characteristics, it provides the most accurate and complete representation of national PAHs emission sources. Secondly, while previous studies estimated emissions at the national scale, this study developed a detailed regional-level emission inventory at the provincial and local levels. Understanding emission characteristics at the regional level facilitates the establishment of appropriate management policies for reducing emissions. Thirdly, while previous studies focused solely on benzo(a)pyrene, in this study, an emission inventory for the major 16 PAHs was developed to expand management criteria to include other compounds. PAHs are emitted as over 100 different compounds. The US EPA and the International Agency for Research on Cancer (IARC) have assessed the carcinogenic risk of those PAHs through risk evaluations. Based on the evaluation, 16 specific PAHs requiring special management and regulation were adopted (US EPA, 1997). Additionally, seven among the 16 PAHs are classified as "7 PAHs" due to their carcinogenic properties, and they are managed specially (US EPA, 1996). In this study, an inventory for the same 16 PAHs was established, and the names and molecular structures of the corresponding substances and whether they are classified as 7 PAHs can be found in Table S1(Supplement).

Detailed information regarding the data used and the applied methodology is provided in Section 2. Following the construction of the PAHs inventory, emissions by compound, emission source, and region were estimated and evaluated to understand the characteristics of PAHs emissions in Korea. Subsequently, the developed inventory was then evaluated through comparison with previous studies and an uncertainty assessment. The results and key findings of this study can be found in Sections 3 and 4.

2. Research data and methodology

2.1. Research framework

Fig. 1 presents the research flow for developing a PAHs emission inventory for Korea. Initially, an emission source classification system was specifically defined for the PAHs emission inventory by categorizing the sources of PAHs among all emission sources classified in CAPSS. These sources were subsequently divided into two groups based on the emission calculation method applied: Activity EF (Emission Factor-Based) and Speciation Profile-Based approaches. Following this reclassification, the required input data were collected, and emission calculations were conducted accordingly. For the Activity EF-Based group—which includes most *area sources* and *point sources*—emissions were estimated using the basic equation provided in the IPCC 2006 Guidelines, where emissions are calculated as the product of activity data and emission factors. In contrast, for the Speciation Profile-Based group, emissions were estimated by applying chemical speciation profiles to existing air pollutant emission data. This group includes *mobile sources* and the *solvent use sector*. For *mobile sources*, equations from the U.S. EPA's Motor Vehicle Emission Simulator (US EPA, 2020) were employed. For the *solvent use sector*, chemical speciation profiles were applied based on data from EPA SPECIATE 5.3 (US EPA, 2023).

Using this methodology, the emissions of PAHs in Korea were estimated for the year 2017 by pollutant, sector, and province. Subsequently, the emissions and characteristics of PAHs in Korea were analyzed. Verification was then conducted by comparing the results of this study with the PAHs emissions data from the Korean PAHs emission inventory developed using 1995 as the base year (Cho et al., 2000). In addition, the PAHs emissions from Korea in the global-scale emission inventory, EDGAR (Crippa et al., 2022), were compared with the emissions estimated in this study to examine whether the PAH emissions and characteristics in Korea were accurately reflected in the EDGAR inventory. Finally, an uncertainty assessment of the emission estimates was performed using error propagation equations.

2.2. Emission sources classification

The emission source classification system for the PAHs emission inventory is primarily based on the CAPSS classification system. Additionally, since CAPSS provides essential statistical data such as activity data and emission factors, it is more efficient to gather the required data for developing the PAHs emission inventory. This approach will be beneficial for maintaining consistency and reliability, even when integrating the PAHs emission inventory developed in this study with CAPSS in the future.

CAPSS classifies emission sources into four tiers: Tier 1 (13 categories), Tier 2 (42 categories), Tier 3 (187 categories), and Tier 4 (over 1000 categories). Emissions were calculated using all tiers up to Tier 4, and for similar sectors among the more than 1000 categories in Tier 4, the same emission factors were applied. Fuels are categorized into 14 types, including B-A, B-B, B-C, LNG, LPG, Diesel, Biomass, Waste, Hydrogen, Kerosene, Anthracite, Bituminous coal, Jet-fuel, and Gasoline. CAPSS provides region-specific data at city, county, and district levels.

Each emission source up to Tier 4 under the CAPSS classification system was assessed to determine their inclusion in the PAH emission inventory. While PAHs are primarily known to be emitted from combustion-related sources (Park et al., 2010), it has also been reported that certain PAHs can be released in volatilized form during Solvent Use processes (US EPA, 1999a). Accordingly, a total of 11 emission sources were selected at the Tier 1 level: *energy production, non-industry, manufacturing industry, industrial process, energy transport and storage, solvent use, on-road mobile, nonroad mobile, waste disposal, other area source,* and *biomass burning*. Table 1 presents Tier 1 and Tier 2 emission sources and their corresponding fuel types and indicates whether the

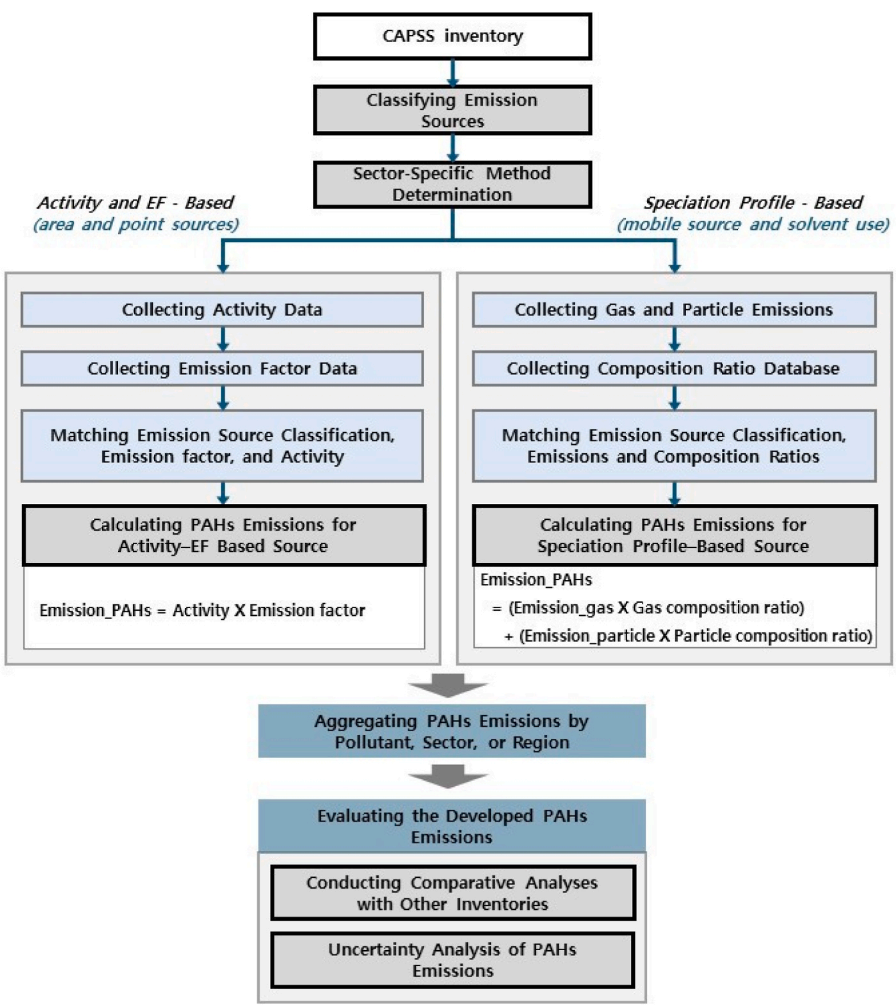

Fig. 1. Research flow for developing and evaluating PAHs Emission inventory in Korea.

Table 1
Emission source sectors and fuel types in the CAPSS (Tier 1 and Tier 2).

Sectors			Fuels	PAHs emissions
	Tier1	Tier2		
1	*energy production*	*public power generation facilities, district heating facilities, petroleum refining facilities, solid fuel conversion facilities, private power generation facilities*	B-A, B-C, LNG, LPG, Diesel, Other, Kerosene, Anthracite, Bituminous coal	○
2	*non-industry*	*commercial and public institution facilities, residential facilities, agricultural, livestock and fisheries facilities*	B-A, B-B, B-C, LNG, LPG, Diesel, Other, Kerosene, Anthracite	○
3	*manufacturing industry*	*combustion facilities, process, other*	B-A, B-B, B-C, LNG, LPG, Diesel, Other, Kerosene, Anthracite	○
4	*industrial process*	*petroleum products industry, steelmaking industry, non-ferrous metal industry, inorganic chemical products manufacturing industry, organic chemical products manufacturing industry, the wood and pulp manufacturing industry, food and beverage processing, ammonia consumption, other manufacturing industry*	[a]	○
5	*energy transport and storage*	*gasoline supply*	[a]	○
6	*solvent use*	*painting facilities, cleaning facilities, laundry facilities, other organic solvent*	[a]	○
7	*on-road mobile*	*passenger car, taxi, van, bus, truck, special car, rv, two-wheeled car*	CNG, LPG, Diesel, Hybrid, Gasoline	○
8	*nonroad mobile*	*ship, airline, agricultural machinery, construction equipment, military equipment, railroad*	B-A, B-B, B-C, Diesel, Kerosene, Jet-fuel, Gasoline	○
9	*waste disposal*	*incineration of waste, other waste disposal*	[a]	○
10	*agriculture*	*fertilizer-use agricultural land, manure management*	[a]	x
11	*other area source*	*natural sources, wildfires, structure fires, wetlands, animals, other*	[a]	○
12	*fugitive dust*	*road re-fugitive dust, tire abrasion, construction work, bare land, loading and unloading, agricultural activities, livestock activities, waste disposal, unpaved road re-fugitive dust*	[a]	x
13	*biomass burning*	*open burning, incineration of agricultural residues, grilled meat and fish, wood stove and boiler, furnace, charcoal kiln*	[a]	○

[a] Emission sources were not categorized by fuel type.

source was selected for building a PAHs emission inventory.

2.3. Calculation method of PAHs emissions and data collection

2.3.1. Activity and EF-based method

For Activity EF-Based method, Equation (1) (IPCC, 2006; US EPA, 2004) was applied, where "E" represents the emissions, calculated as the product of "A" and "EF." In this context, "A" represents the activity data, which is the amount of activity generating emissions, and "EF" represents the emission factor, which is the amount of air pollutants emitted per unit activity of the emission source.

$$\mathbf{E = A \times EF} \tag{1}$$

The activity data was acquired from CAPSS and supplemented with data from government databases, industry reports, and business reports. CAPSS provides activity data and emission factors for each emission source to estimate emissions for nine 'Criteria Air Pollutants (CO, NO_x, SO_x, TSP, PM_{10}, $PM_{2.5}$, NH_3, VOC, and BC). Since most PAHs are emitted during the combustion of fossil fuels and biomass, the activity data from CAPSS can be used to estimate PAH emissions from the same emission sources. The latest version of CAPSS, CAPSS 2017 (released in October 2020), was obtained and utilized for this study.

Regarding emission factors, there are almost no studies in Korea (Cho et al., 2000). Therefore, PAHs emission factors from previous studies conducted outside of Korea were collected and utilized. PAHs emission factors without emission control efficiency or with minimal emission control technology were used due to limited information availability on emission control efficiency and its application status in Korea. In other words, the primary sources of emission factors applied in this study were the US EPA's AP-42 (Compilation of Air Pollutant Emissions Factors section 13.2.1) (US EPA, 2021; U.S. Environmental Protection Agency, 1995a; US EPA, 1995b; US EPA, 1999b) and L&E (Locating and Estimating Air Toxic Emissions from Sources of Polycyclic Organic Matter) (US EPA, 2016). AP-42 provides emission factors and process information for over 200 sources of air pollutants, while L&E offers emission factors for hazardous substances such as Polycyclic Organic Matter (POM) by emission source. For data not obtained from the above two sources, previous research papers on PAHs emission factors were referenced (e.g., El-Badry, 2010; Ryu, 2013). The sources of emission factors by sector are summarized in Table S2(Supplement.)

In cases where the collected emission factors were values from a more detailed classification than the classification system defined in section 2.3, some efforts were made to refine the existing classification system. For example, within the *gas station (including refueling) sector* (Tier 3) of *gasoline supply* (Tier 2) under *energy transportation and storage* (Tier 1), the emission factor of gas stations varies by approximately 10 times depending on the presence or absence of oil vapor recovery facilities. Therefore, in this study, considering the "mandatory installation of oil vapor recovery facilities (MOE, 2008)," different emission factors were applied by categorizing areas into "special-measures area or air quality control area" and other areas.

Then, efforts were made to align source-specific emission factors and units of activity data for the calculation of emissions. National standard methods and statistical data were employed for unit conversion. For instance, when converting mass into energy, the "Energy Calorific Value Conversion Standard" of the Korea Energy Economics Institute (KEEI, 2022) was applied, and the corresponding values can be found in Table S3(Supplement). In the case of the *forest fire source*, to convert the forest fire damage area, which is a unit of activity, into the amount of fuel, data from Choi et al. (2015) were utilized. This data provides estimation data for the fuel load per unit area for major forest types in the 6th National Forest Resource Survey, which was conducted from 2011 to 2015. (Korea Forest Service, 2018). Additionally, the Korea Energy Agency's 2017 New and Renewable Energy Statistics (KEA, 2018) were used. The values applied in the *forest fire source* can be found in Table S4(Supplement).

2.3.2. Speciation Profile-Based Method

In general, air pollutant emissions are calculated as the product of activity data and emission factors. However, this conventional approach is not suitable for estimating PAHs emissions from *mobile sources* and *the solvent use sector*. For mobile sources, emission levels can vary significantly depending on factors such as vehicle size, fuel type, vehicle category, driving conditions, and driving behavior. Yet, the PAHs emission factors provided by sources such as AP-42 and L&E are generalized values based on representative vehicle and fuel types, making it difficult to account for these variations adequately. The *solvent use* is another representative case where activity-based estimation is challenging. It is difficult to obtain customized emission factors, and the limited availability of applicable emission factors contributes to high uncertainty in emission estimates. Therefore, in this study, a Speciation Profile-Based Method was applied using chemical speciation profiles to better reflect the characteristics of these emission sources.

For mobile source, this study adopted the methodology of the US EPA's MOtor Vehicle Emission Simulator Version 3 (MOVES 3), which accurately estimates emissions based on vehicle characteristics. MOVES is the EPA's mobile source emissions model that calculates emissions based on the vehicle's speed in seconds and Vehicle-Specific Power (VSP) estimation categorized by vehicle type. This method distinguishes between particulate and gas-phase emissions and estimates emissions by multiplying the emissions of air pollutants (VOC, $PM_{2.5}$, and OC) by the corresponding fraction values of PAHs emissions for each emission source (US EPA, 2020). Although these fraction values are based on U.S. vehicle fleet data, in this study, it was assumed that Korea's vehicle technologies—being significantly influenced by U.S. emission standards—are sufficiently similar, and therefore, the values were applied accordingly. The emission calculation formula for *on-road mobile* is shown in Equation (2), while the formula for *nonroad mobile* is shown in Equation (3). The distinction lies in replacing the PE value with OC emissions for *on-road mobile* and $PM_{2.5}$ emissions for *nonroad mobile*.

$$\boldsymbol{E_{PAHs\_on}} = \boldsymbol{E_{voc}} \times \boldsymbol{GP} + \boldsymbol{E_{oc}} \times \boldsymbol{PP} \tag{2}$$

E_{PAHs_on}: Emission of PAHs for *on-road mobile*
E_{voc}: Emission of VOC
GP: Gaseous Phase Emission Fractions (PAHs/VOC)
E_{oc}: Emission of OC
PP: Particulate Phase Emission Fractions (PAHs/OC)

$$\boldsymbol{E_{PAHs\_non}} = \boldsymbol{E_{voc}} \times \boldsymbol{GP} + \boldsymbol{E_{PM2.5}} \times \boldsymbol{PP} \tag{3}$$

E_{PAHs_non}: Emission of PAHs for *nonroad mobile*
E_{voc}: Emission of VOC
GP: Gaseous Phase Emission Fractions (PAHs/VOC)
$E_{PM2.5}$: Emission of $PM_{2.5}$
PP: Particulate Phase Emission Fractions ($PAHs/PM_{2.5}$)

The emissions of air pollutants, including E_{voc}, E_{oc}, and $E_{PM2.5}$ were obtained from CAPSS 2017. For gaseous air pollutant emissions, VOC emissions were used, while for particulate air pollutant emissions, OC emission values were used for *on-road mobile*, and $PM_{2.5}$ emission values were used for *nonroad mobile*. Since national official OC emission data are not available for the *nonroad mobile*, OC emissions were derived by multiplying the national official $PM_{2.5}$ emissions data by the split factors provided in the AERO7 aerosol module (US EPA, 2019). The $PM_{2.5}$ to OC split factors from AERO7 are shown in Table S5(Supplement).

GP and PP, representing the ratio of PAH emissions to emissions of gaseous or particulate air pollutants, were obtained from MOVES3. As illustrated in Table 2, MOVES 3 offers GP and PP values for 16 PAH compounds categorized by sector, fuel, and type, allowing different values to be applied depending on the characteristics of each emission source. For example, the values for *on-road mobile* 2007–2009 diesel engines are provided in Table S6(Supplement).

For *solvent use*, PAHs emissions were estimated using the U.S. EPA's chemical speciation database, SPECIATE, which provides detailed composition profiles of VOCs and particulate matter from various emission sources. This study utilized the GAS profile data from SPECIATE. Since direct ratios of PAHs to VOCs are not available for *solvent use*, the estimation was performed using both the VOC-to-TOG (Total Organic Gas) ratio and the PAHs-to-TOG fraction. As described in Equation (4), VOC emissions (E_{voc}) from CAPSS 2017 were first converted to TOG emissions using the VOC/TOG ratio (*CF*). Then, the PAHs/TOG fraction (*GP*) from SPECIATE was applied to the estimated TOG emissions to calculate the final PAHs emissions ($E_{PAHs\_solvent}$) from *solvent use*.

Table 2
Categories for providing gas/particle partitioning factors (GP and PP) in MOVES.

Sector	Fuel	Type
on-road mobile	Gasoline Exhaust	Vehicles Operating on Fuel Blends Containing 0–15 Percent Ethanol
		Vehicles Operating on Fuel Blends Containing <20 Percent Ethanol
		Vehicles Operating on Fuel Blends Containing 70–100 Percent Ethanol
	Diesel	Pre-2007 Diesel Engines.
		2007–2009 Diesel Engines.
		2009+ Diesel Engines
	Compressed Natural Gas (CNG)	[a]
nonroad mobile	Gasoline Exhaust	[a]
	Diesel	Tier1
		Tier2
		Tier3
		Tier4
	Compressed Natural Gas (CNG)	[a]
	Liquefied Petroleum Gas	[a]

[a] Detailed type classification does not exist.

$$\boldsymbol{E_{PAHs\_solvent}} = \boldsymbol{E_{voc}} \div \boldsymbol{CF} \times \boldsymbol{GP} \tag{4}$$

$E_{PAHs\_solvent}$: Emission of PAHs for *solvent use*
E_{VOC}: Emission of VOC
CF: Conversion Factor from Total Organic Gases to Volatile Organic Compounds (VOC/TOG)
GP: Gaseous Phase Emission Fractions (PAHs/TOG)

2.4. Evaluation processes

2.4.1. Comparison with the previous PAHs emission inventory of Korea

The PAHs emission inventory developed in this study was compared with the inventory previously constructed by Cho et al. (2000) for Korea. Cho et al. (2000) developed the inventory for 16 types of PAHs using data from 1995. Table 3 summarizes the main differences between the two inventories. Cho et al. (2000) adopted the classification system of the US EPA, consisting of two main categories: *fuel consumption* and *industrial process and other sectors*. The *fuel consumption sector* was categorized into industrial, commercial, and residential sectors, with emissions from each sector calculated based on the '1995 Energy Survey Report in Korea' to account for combustion in heating facilities and internal combustion engines. The emission sources in *industrial process and other sources* are highly diverse. Consequently, to calculate emissions for these sources, activity data had to be collected according to the specific emission sources. However, due to insufficient data availability, emissions for these sources were only calculated for industries where relevant data were accessible. In other words, due to the inclusion of only some emission sources from *industrial process and other sources* in the calculation process and the lower accuracy of the data collected at the time of the study, the estimate of emissions may have been underestimated compared to the actual emissions.

In comparing emissions between the PAHs inventory developed in this study and the existing inventory, only commonly calculated sectors

Table 3
The comparison of inventories between Cho et al. (2000) and this study.

Inventory	Cho et al. (2000),[a]	This study
Base year	1995	2017
Region	Korea (National level)	Korea (Province level)
Pollutant	Total 7 PAHs, Total 16PAHs (not providing emissions of each pollutant)	Each 16 PAHs
Source (Tier 1)	***fuel combustion***	***energy production***
		non-industry
		manufacturing industry
		on-road mobile
		nonroad mobile
	industry process and other	***industrial process***
		waste disposal
		biomass burning
	Not Available in Cho et al. (2000)	*solvent use*
		other area source
		energy transport and storage

[a] The data from Cho et al. (2000) was not used to develop the PAHs emission inventory in this study.

were considered for both inventories. This approach aimed to minimize errors resulting from the underestimation of *industrial process and other sectors* in previous studies. The common sectors, including *energy production, non-industry, manufacturing industry, on-road mobile, nonroad mobile, industrial process, waste disposal,* and *biomass burning,* were identified based on the sectors classified in this study, as shown in Table 3. *Sectors that are covered by both* Cho et al. (2000) *and this study are indicated in bold in* Table 3. The sectors "*other area source*", "*energy transport and storage*" and "*solvent use*" were excluded from the comparison, as they were not covered in Cho et al. (2000).

2.4.2. Comparison with the PAHs emission inventory of Korea developed by EDGAR

The analysis aimed to confirm the similarity of the values by comparing Korea's PAHs emissions presented in overseas studies with the values estimated in this study. The subject of comparison was selected as EDGAR (Crippa et al., 2022) by EEA. EDGAR provides independent emission estimates compared to those reported by European Member States or by Parties under the United Nations Framework Convention on Climate Change (UNFCCC), using international statistics and a consistent IPCC methodology (UNEP, 2023). These emissions have been actively used as data for global-scale air quality modeling.

EDGARv6.0 provides greenhouse gas and air pollutant emissions data from 1970 to 2018, including data on four PAHs: Benzo(a)pyrene, Indeno (1,2,3-cd) pyrene, Benzo(b)fluoranthene, and Benzo(k)fluoranthene. The emissions inventory is created at a resolution of 0.1° × 0.1°. As this inventory provides emissions according to IPCC sector codes, mapping was necessary to compare sector emissions with those in this study. The "HTAP_v3 sector mapping for IPCC categories (EU, 2022)" was utilized to match EDGAR's sectors into eight sectors of this study: *international shipping, aviation, energy, industry, ground transportation, housing, waste,* and *agriculture*. The "HTAP_v3 sector mapping for IPCC categories" is shown in Table S7(Supplement).

2.4.3. Uncertainty analysis

To quantitatively assess the reliability of the emission estimates, an uncertainty analysis was conducted using the Error Propagation Method, one of the techniques recommended in the IPCC Guidelines (IPCC, 2006) This method statistically combines the individual uncertainties of key input variables (e.g., activity data and emission factors) to estimate the uncertainty of emissions by sector as well as for the total emissions.

The error propagation method assumes that all input variables are mutually independent and does not account for any correlation between variables. The analysis was carried out in two steps. In the first step, the relative uncertainties of activity data and emission factors were combined to calculate the uncertainty for each individual sector, and a factor of **1.96** was applied to reflect a **95 % confidence level.**

This approach is based on the statistical characteristics of lognormal distributions and is particularly suitable for cases where emission estimates are derived from the multiplication of two input variables, such as activity data and emission factors. While conventional error propagation methods often involve the simple addition or averaging of uncertainties, such approaches may underestimate the total uncertainty when applied to multiplicative relationships, where the effects of input errors can compound. Equation (5) accounts for this structural characteristic by combining the relative uncertainties of each input variable in a way that reflects their interactive impact. As a result, it enables a more conservative and reliable estimation of uncertainty, helping to prevent underestimation in emission calculations.

In the second step, the overall uncertainty of the total emissions for the base year was calculated using the sectoral uncertainties derived from Equation (5). This was done by applying Equation (6), which is based on the Root Sum of Squares (RSS) method, with the emission share of each sector used as a weighting factor.

$$\boldsymbol{U_i} = \mathbf{1.96} \times \sqrt{\left(\mathbf{1} + \boldsymbol{U^2_{EF\ for\ i}}\right)\left(\mathbf{1} + \boldsymbol{U^2_{AD\ for\ i}}\right) - \mathbf{1}} \quad (5)$$

$\boldsymbol{U_i}$: Absoulte uncertainty of emission for sector i
$\boldsymbol{U_{EF\ for\ i}}$: Relative uncertainty of emission factor for sector i
$\boldsymbol{U_{AD\ for\ i}}$: Relative uncertainty of activity for sector i

$$\boldsymbol{U_T} = \frac{\sqrt{\sum_{i=1}^{n} (\boldsymbol{U_i} \times \boldsymbol{x_i})^2}}{\sum_{i=1}^{n} \boldsymbol{x_i}} \quad (6)$$

$\boldsymbol{U_T}$: Total uncertainty of national emissions
$\boldsymbol{U_i}$: Absoulte uncertainty of emission for sector i
$\boldsymbol{x_i}$: Emission of PAHs for sector i

The uncertainty of activity data was derived from the relative uncertainty ranges (confidence intervals, %) provided in KOSAE (2023), while that of emission factors was obtained from the EMEP/EEA Guidelines (2023) (see Tables S8 and S9 in the Supplement). Both sources present uncertainty values based on emission sector and data reliability ratings, which were used to assign appropriate uncertainty values in this study.

For emissions estimated using the activity and emission factor-based approach, activity data uncertainties were directly adopted from KOSAE's sector-specific assessments. For emission factors, when the EMEP/EEA guidelines specified a reliability rating, the midpoint of the corresponding uncertainty range was applied. In particular, Rating E represents an "order of magnitude" level of uncertainty, and a symmetric range of ±900 % was applied based on Streets et al. (2003). Where no rating was available, one was assigned based on the source and characteristics of the data, and the corresponding uncertainty midpoint was used to ensure consistency.

For emissions calculated using the Speciation Profile-Based method, air pollutant emissions from CAPSS were treated as activity data, and the speciation profiles were considered emission factors. Uncertainty for the base emissions followed KOSAE (2023), while uncertainty for the speciation profiles was sourced from EPA SPECIATE. In the absence of specific uncertainty values, the maximum default value of ±99 % was applied. Additional sector- and pollutant-specific uncertainties from Kim and Jang (2014), based on the 2017 CAPSS inventory, are summarized in Table S10 (Supplement).

3. Results

3.1. Calculated PAHs emissions for Korea

3.1.1. PAHs emissions by pollutant

The total emission of 16 PAHs in 2017 was 1.26 Gg/yr. Table 4 summarizes the emission calculation results and proportions for each pollutant in order of molecular weight, from Naphthalene, which has the smallest molecular weight, to Dibenz (a,h)anthracene. Emissions of low-molecular PAHs consisting of 2 or 3 benzene rings are generated more than those of high-molecular PAHs consisting of 4–6 benzene rings. In particular, it can be seen that the combined emissions of Naphthalene and Phenanthrene account for 63.8 % of the total. The sum of 7 PAHs emissions is 3.3 % of the total emissions. Although the amounts are not large, these 7 PAHs are carcinogenic pollutants, and this amount cannot be ignored.

3.1.2. PAHs emissions by sector

Fig. 2 depicts a pie graph illustrating the share (%) of emissions of 16 PAHs by sectors. Observing the pie chart on the left, emissions from the *industrial process* sector were the highest at 34 %, followed by *nonroad mobile* and *waste disposal* at 15 % and 11 %, respectively. *on-road mobile sector* ranked next with 10 %, indicating that mobile and waste sources are significant contributors to overall emissions. The major emission sources in the *industrial process* sector were identified by calculating each Tier 2 share of total emissions. Therefore, improving processing technology and strengthening regulations in the *petroleum product industry* are believed to be effective in reducing Korea's PAHs emissions. Further details can be found in Table S11(Supplement).

Fig. 3 illustrates a pie graph representing the share (%) of emissions by sector for the 7 PAHs. Emissions from *other area source* were the highest at 39 %, followed by the *industrial process sector* and *biomass burning sector*. To identify major emission sources of the 7 PAHs among *other area source* emission ratios at Tier 2 level were calculated and depicted in the pie graph on the right side of Fig. 3. In the case of the 7 PAHs, emissions from forest fires accounted for 99.5 % of emissions from *other area source*. Detailed results can be found in Table S12 (Supplement).

As shown in section 3.1.1, the total emissions of Naphthalene (NaP), Phenanthrene (Phen) and Pyrene (Pyr) accounted for 73.9 % of the total emissions. The 7 PAHs are carcinogens that necessitate special management. Therefore, further examination was conducted to assess the proportions of these pollutants by emission sector. Fig. 4 displays the emissions by sector for each substance for these ten PAHs in a bar graph. Among them, the 7 PAHs are plotted on separate graphs within the inner boxes, with different scales utilized. This offers insight into the emissions of the 7 PAHs by sector, which exhibit lower emission levels compared to NaP, Phen and Pyr.

NaP emissions were highest in the following order: *energy transport and storage*, *on-road mobile*, and *nonroad mobile*. 81.6 % of Phen emissions came from *industrial process*, of which 97 % originated from the *petroleum products industry*. This source encompasses processes for producing or processing petroleum products such as gasoline, kerosene, and diesel oil. For Pyr, 85.7 % of total emissions were found to originate from *biomass burning* and *on-road mobile*.

As presented in Fig. 4, *other area source* was the primary contributors to the emissions of the 7 PAHs. However, the emissions of Benzo(a) pyrene (BaP), which is known to pose a particularly high risk to human health, were predominantly from the *waste disposal sector*, accounting for approximately 36.8 % of BaP emissions. In general, emissions of the 7 PAHs were relatively high from sources lacking pollution control facilities, such as *other area source*, *waste disposal*, and *biomass burning*. These findings suggest that pollution control facilities are not only effective in reducing atmospheric pollution emissions but also in mitigating the emissions of toxic substances, including the 7 PAHs.

3.1.3. PAHs emissions by region

The regional distribution of emissions can be seen in Fig. 5. Fig. 5(A) illustrates the distribution of total emissions for the 16 PAHs by region, revealing high emission levels in the provinces of ULSAN, JEONNAM, CHUNGNAM, and GYEONGGI. To examine the main sources contributing to these emissions, an analysis was conducted on the regional distribution of emissions by key sources. The three major sources selected were the *industrial process*, which had the highest proportion of the 16 PAHs emissions; the *energy transport and storage*, which had significant emissions on a national scale; and *other area source*, which had the most emissions of the 7 PAHs. Fig. 5(B)–(C), and Fig. 5(D) each depict the regional distribution of emissions for these major sectors. Detailed information on regional emissions and their proportions for all sectors, as well as for each of the three major sectors, can be found in Table S13(Supplement).

In Fig. 5(B), the *industrial process sector* exhibited the highest emissions in ULSAN, JEONNAM, and CHUNGNAM. These emissions are primarily associated with petrochemical complexes, specifically ULSAN's Mipo National Industrial Complex, JEONNAM's Yeosu National Industrial Complex, and CHUNGNAM's Daesan Petrochemical Complex as marked with stars in Fig. 5(B). This finding aligns with the analysis discussed in Section 3.1.2, which recognized the petrochemical industry as the major source of emissions in the *industrial process*.

As shown in Fig. 5(C), emissions in the *energy transport and storage sector* are notably high across the nation. This can be attributed to the widespread influence of gas stations and oil refineries, as pipelines

Table 4
PAHs emissions by pollutant in 2017.

# of Benzene Ring	Pollutant	Molecular weight (g/mol)	Emissions (Mg/yr)	Ratio of PAH (%)	7 PAHs (Y/N)	Ratio of 7 PAH (%)
2	Naphthalene	128.1	469.37	37.3	N	-
3	Acenaphthylene	152.1	110.22	8.7	N	-
3	Acenaphthene	154.2	20.94	1.7	N	-
3	Fluorene	166.2	27.81	2.2	N	-
3	Phenanthrene	178.2	334.26	26.5	N	-
3	Anthracene	178.2	14.97	1.2	N	-
4	Fluoranthene	202.3	93.78	7.4	N	-
4	Pyrene	202.3	126.86	10.1	N	-
4	Benzo(a)anthracene	228.3	7.55	0.6	Y	18.1
4	Chrysene	228.3	7.22	0.6	Y	17.3
5	Benzo(b)fluoranthene	252.3	5.47	0.4	Y	13.1
5	Benzo(k)fluoranthene	252.3	4.64	0.4	Y	11.1
5	Benzo(a)pyrene	252.3	10.74	0.9	Y	25.7
6	Indeno (1,2,3-cd)pyrene	276.3	3.11	0.2	Y	7.4
6	Benzo (ghi)perylene	276.3	19.69	1.6	N	
5	Dibenzo (a,h)anthracene	278.4	3.05	0.2	Y	7.3
–	**Total 16 PAHs**	-	1259.6	**100**	-	
–	**Total 7 PAHs**	-	41.77	**3.3**	-	**100**

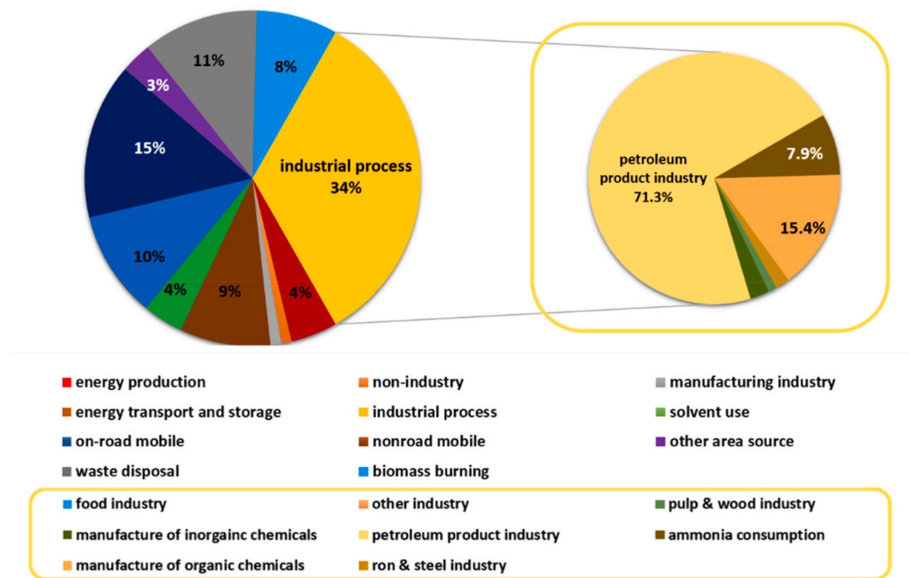

Fig. 2. 16 PAHs emissions by sector.

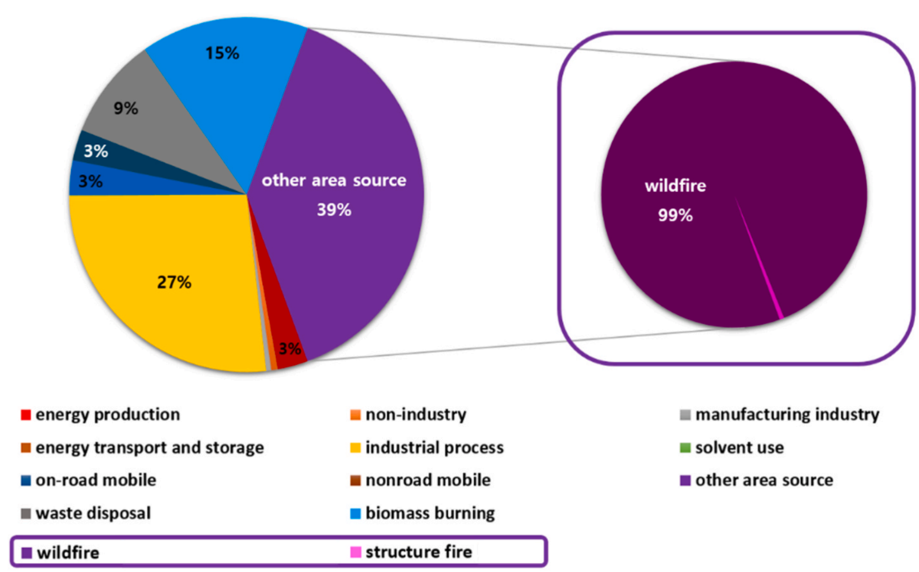

Fig. 3. 7 PAHs emissions by sector.

extend across the country. The highest emissions are recorded in GYEONGGI Province, where facilities such as the Pangyo Oil Storage depot and the Daehan Oil Pipeline Corporation are located. These facilities are responsible for supplying oil to six depots in Korea, which is analyzed to be a contributing factor to the high emissions observed.

Fig. 5(D) shows the regional emission distribution of *other area source*, considered the primary source of emissions for the 7 PAHs. It was observed that GANGWON Province had the largest emissions. Considering the large wildfire that occurred in Gangneung-Samcheok-Sangju in 2017, resulting in a total affected area of 1479.7 ha, and the fact that 80.8 % of the nationwide wildfire area in 2017 was in GANGWON Province (Korea Forest Service, 2018), a parallel can be drawn to the data showing that 97.5 % of emissions from Other Area Source in Table S11(Supplement) are due to wildfires. For reference, the area affected by wildfires in 2017 was 1480 ha, which is actually lower than the average annual damage area over the past ten years (2015–2024), approximately 4003 ha—a reduction of about 63.0 % (Forest Service, 2025). Considering the overall trend, this figure is unlikely to be an excessive value.

3.2. Evaluating the developed PAHs emission inventory

3.2.1. Inter-comparison with other inventories

3.2.1.1. Comparison with the PAHs inventory previously developed in Korea. After calculating the 2017 PAH emissions of Korea in this study, the results were compared with the results of the previous study by Cho et al. (2000). Fig. 6 is a graph comparing the emissions of the two inventories. In the previous study, the emissions of 16 PAHs in 1995 were 780 Mg/yr, which is 282 Mg/yr less than the total emissions of 1062 Mg/yr in this study. The difference in emissions between these two studies appears to be due to variations in the proportion of energy consumption between the two reference years (2017 vs. 1995).

Fig. 7 illustrates the comparison of energy consumption between 1995 and 2017. In 1995, 130.6 Mtoe of energy was supplied, while in 2017, the supply increased to 253.1 Mtoe, representing a difference of

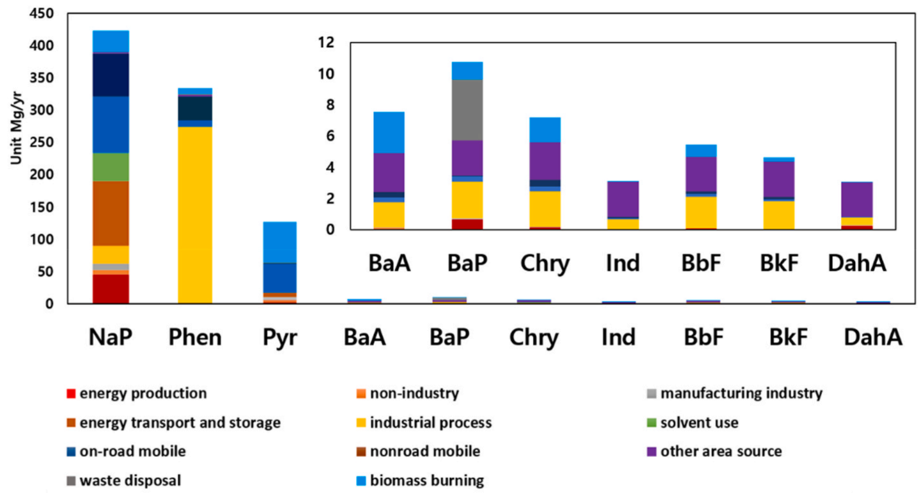

Fig. 4. PAHs emissions of major concern pollutants in 2017 (unit: Mg/yr).

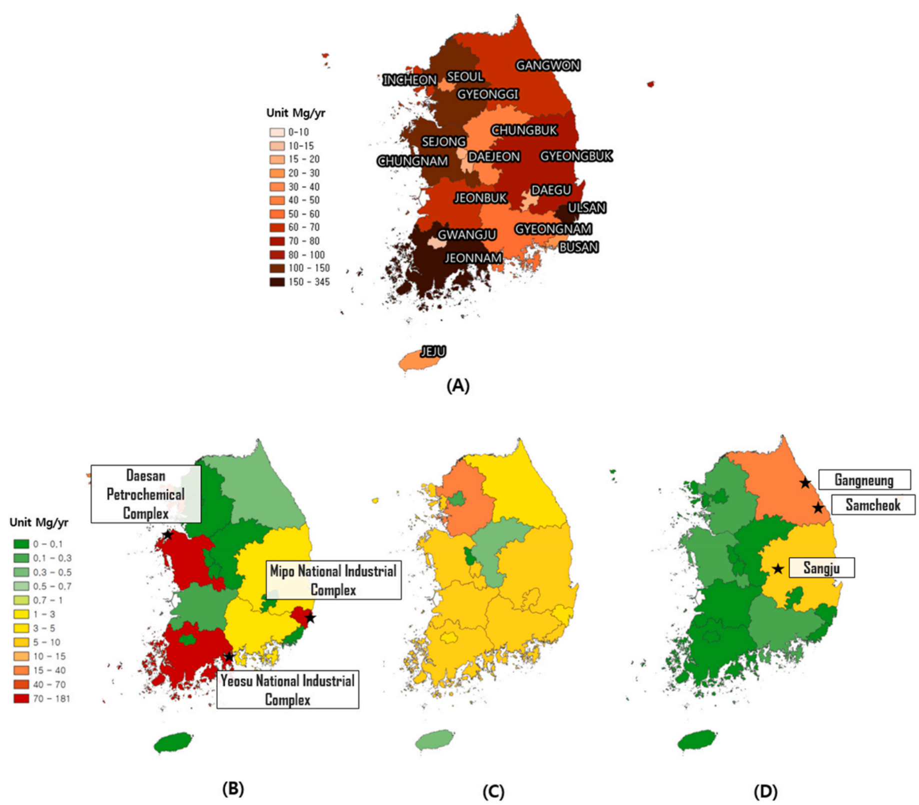

Fig. 5. Regional Emissions of 16 PAHs from Major Sectors in 2017 ((A): All Sectors, (B): industrial process, (C): energy transport and storage, (D): other area source).

1.94 times. Specifically for coal, the energy supply was 27.5 Mtoe in 1995 and 86.2 Mtoe in 2017. In the case of oil, the supply was 94.0 Mtoe in 1995 and 119.3 Mtoe in 2017. As for LNG, the supply increased from 9.2 Mtoe in 1995 to 47.5 Mtoe in 2017. When examining the fuel consumption ratios for the two years, the proportion of oil consumption significantly decreased from 72 % in 1995 to 47 % in 2017. Oil consistently represented the largest share of the fuel supply in both years. Comparing the differences in energy supply (1.94 times) and oil supply (1.27 times) with the difference in PAH emissions between the two studies (1.5 times), the results of the studies were interpreted to be consistent with trends in energy usage.

3.2.1.2. Comparison with the PAHs inventory developed by EDGAR. The emissions data of Korea from EDGAR, which is a global emission inventory, were compared with the emissions results of this study. Both are emission estimates for the year 2017. It was possible to compare the emissions of the 4 PAHs including BaP, Ind, BbF, and BkF, and the comparison results are shown in Table 5. The emissions of BaP, Ind, BbF, and BkF from EDGAR were 1.9, 2.9, 5.1, and 2.2 times higher, respectively, than the emissions from this study.

To identify the cause of this difference, a comparison of sectoral emission ratios for the four PAHs was conducted, distinguishing between the *residential* and *other sources* as shown in Fig. 8. It was confirmed that emissions from the *residential sector* in EDGAR were

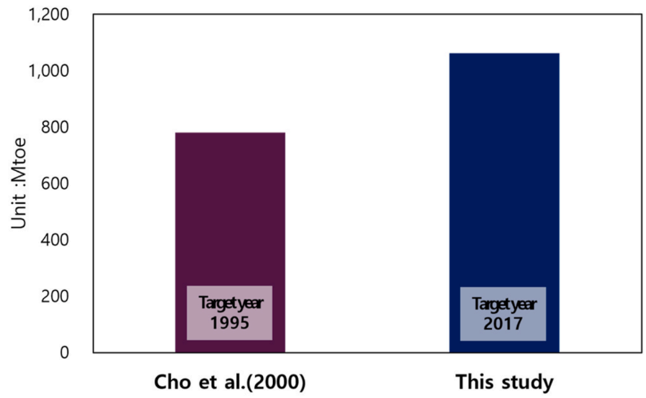

Fig. 6. Comparison of emissions with Cho et al. (2000).

higher than this study. In this study, the *residential sector* ratios for BaP, Ind, BbF, and BkF were 10.6 %, 1.2 %, 14.3 %, and 6.3 %, respectively, while in EDGAR, the *residential sector* ratios were much higher at 62.1 %, 61.9 %, 54.8 %, and 55.8 % for BaP, Ind, BbF, and BkF, respectively.

To investigate the differences in emissions between the inventories, the activity data and emission factors were compared. To assess the similarity in activity data, BC and NO_x emissions from CAPSS were compared to those from EDGAR. For NO_x, EDGAR reported 1126 Mt while CAPSS reported 1190 Mt, showing a ratio of approximately 1.05. For BC, EDGAR reported 14.43 Mt while CAPSS reported 15.56 Mt, indicating a similar value with a ratio of around 1.07. Therefore, the differences in activity data between this study and EDGAR were not deemed significant enough to explain the aforementioned results.

Next, a comparison of emission factors was conducted. Since the largest difference in emissions was observed in the *residential sector*, the emission factors of this sector were primarily compared. The emission factors for the *residential sector* used in this study (EPA AP-42, El-Badry et al., 2010; Ryu, 2013) were compared to those from EDGAR referencing the 1.A.4 and 1.A.5 codes (based on the IPCC, 2006 codes in the EMEP/EEA, 2019). In this study, the average emission factors for BaP, Ind, BbF, and BkF were determined to be 0.245 g/Mg, 0.028 g/Mg, 0.503 g/Mg, and 0.228 g/Mg, respectively, and applied accordingly. In EDGAR, ranges are provided for overall emission factors for 16 PAHs and specific emission factors for BaP. So, the average Bap emission factor from EDGAR was compared with the Bap emission factor used in this study. The calculated average value was around 10.0 g/Mg, indicating that the emission factors used in EDGAR were approximately 40.9 times higher than the emission factor of 0.245 g/Mg used in this study. Therefore, it was interpreted that the main reason for the differences in emissions between EDGAR and this study stemmed from the differences in emission factors.

Table 5
PAHs emissions from this study's inventory and EDGAR (Unit: Mg/yr).

Pollutant	EDGAR (2017)	This study	EDGAR (2017)/This study
BaP	20.5	10.7	1.9
Ind	9.3	3.1	2.9
BbF	27.8	5.5	5.1
BkF	10.5	4.6	2.2

3.2.2. *Uncertainty analysis of PAHs emissions*

The overall uncertainty of the 2017 PAHs emission inventory was estimated to ±103.8 %. However, as summarized in Table 6, both absolute and relative uncertainties varied significantly by sector, depending on the characteristics of each source.

The *industrial process sector*, which contributed the largest share of total emissions (26 %), had the highest absolute uncertainty at 667.6 Mg and a relative uncertainty range of ±158 %, indicating a substantial influence on the overall inventory uncertainty. Other major contributors, including *waste disposal* (140.4 Mg), *nonroad mobile* (189.3 Mg), *on-road mobile* (129.6 Mg), and *biomass burning* (98.4 Mg), also showed high relative uncertainties of ±606 %, ±65 %, ±72 %, and ±513 %, respectively. In terms of absolute uncertainty, *waste disposal* and *biomass burning* exhibited particularly large ranges ±850.8 Mg ± 505.4 Mg, respectively).

Conversely, some sectors showed relatively low emissions but very high uncertainty, suggesting low reliability. For instance, *other area source* emitted only 37.9 Mg but had a relative uncertainty of −138 % to +1329 %, and an absolute uncertainty range of ±503.2 Mg. Similarly, *energy production* (±83.0 Mg, ±147 %), *non-industry* (±22.9 Mg, ±178 %), and *manufacturing industry* (±20.6 Mg, ±160 %) were also classified as sectors with high uncertainty and lower data reliability.

In contrast, sectors such as *energy transport and storage* (±24.7 Mg, ±22 %) and *solvent use* (±21.8 Mg, ±45 %) demonstrated relatively lower uncertainty levels, indicating higher data reliability in those categories.

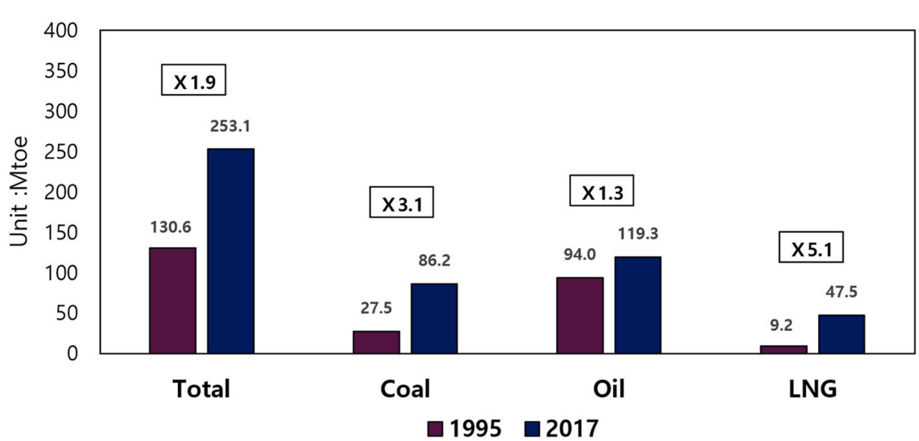

Fig. 7. Primary Energy Supply Comparison (1995 vs. 2017).

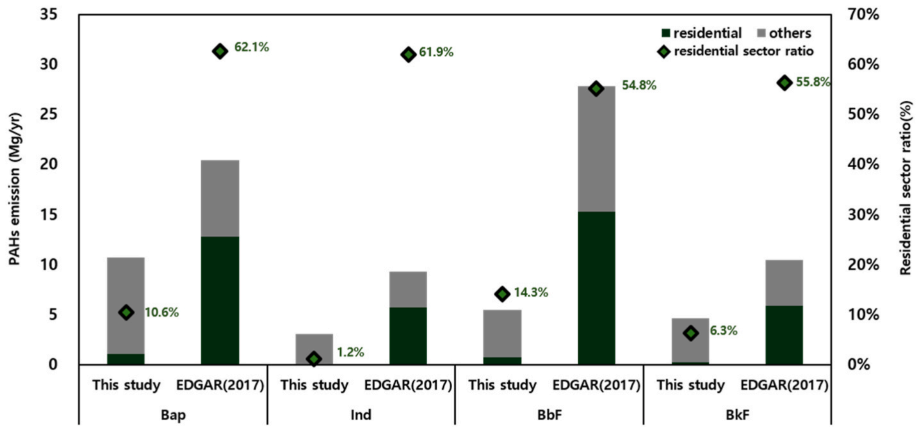

Fig. 8. Emissions of 4 PAHs of this study and EDGAR (Mg/yr).

Table 6
Sectoral uncertainty assessment of PAHs emissions.

Sector	Emission Contribution (%)	Absolute Uncertainty [±Mg]	Relative Uncertainty [±%]	Uncertainty Contribution (%)
energy production	4 %	83.03	147 %	0 %
non-industry	1 %	22.94	178 %	0 %
manufacturing industry	1 %	20.63	160 %	0 %
industrial process	34 %	667.62	158 %	26 %
energy transport and storage	9 %	24.67	22 %	0 %
solvent use	4 %	21.78	45 %	0 %
on-road mobile	10 %	92.92	72 %	1 %
nonroad mobile	15 %	122.96	65 %	1 %
waste disposal	11 %	850.81	606 %	42 %
other area source	3 %	503.22	1329 %	15 %
biomass burning	8 %	505.41	513 %	15 %
Total	100 %	1308.03	**103.8 %**	100 %

4. Conclusions

In this study, a PAHs emission inventory for Korea was developed. Sixteen PAHs were selected, including seven highly carcinogenic ones that require intensive emission management. The base year for collecting various data for emission estimation was 2017, and consistency with Korea's emission inventory for other air pollutants was aimed to be maintained in terms of source categorization, fuel types, and activity data. The methodology for estimating PAHs emissions was adapted and customized to fit the Korean context by referencing US EPA data and relevant studies.

The total annual emissions of 16 PAHs in 2017 calculated using the developed emission inventory were 1259.7 Mg, with 7 PAHs accounting for 41.8 Mg. When compared to the values calculated by Cho et al. (2000) based on 1995, it shows a higher value. It was found that the trend of major energy supply changes between the reference year 1995 and 2017 is similar. Since the inventory developed in this study includes more emission sources compared to previous studies, only emissions in common sectors were compared. It was analyzed that emissions in 2017 were about 1.4 times higher than in 1995. The increase in energy consumption has led to an increase in the emissions of 16 PAHs, indicating the need for reduction policies.

The developed emission inventory allows for estimating emissions by source, providing detailed information at a local level within Korea. This enabled a detailed analysis of PAHs emission characteristics in Korea. The main sector of emissions for the 16 PAHs was *industrial process*, mainly from the *petroleum product industry*. For the 7 PAHs, the main sector was *other area source*, primarily from *wildfires*. Emissions of the 7 PAHs were relatively higher in sectors like *other area source*, *waste disposal*, and *biomass burning*, where pollution prevention facilities are generally lacking. This highlights the importance of pollution prevention facilities not only in reducing emissions but also in mitigating toxicity, underscoring the need to expand such facilities.

Upon comparing the regional emissions of all 16 PAHs, it was observed that ULSAN, JEONNAM, CHUNGNAM, and GYEONGGI had the highest emissions in that order. Analysis of the major source -specific regional emissions revealed that in ULSAN, JEONNAM, and CHUNGNAM, *industrial process* were the primary sources of PAH emissions, while in GYEONGGI, emissions were predominantly from *energy transportation and storage sector*. The total emissions of the 7 PAHs were highest in GANGWON, where wildfires are most prevalent. Due to the regional differences in emission characteristics, it is essential to consider these when devising differentiated approaches for policy-making and regulation of PAHs. It is evident that the PAHs inventory developed in this study can be effectively utilized in this process.

In addition to the comparison with domestic data, an international comparison was conducted using the EEA's EDGARv6.0 database to assess the global consistency and applicability of the developed inventory. In this study, the emission values for PAHs in Korea obtained from the EDGARv6.0 dataset were compared with the values estimated in this study. The emissions for each PAH compound in EDGAR were found to be approximately two to five times higher than those in our study. This discrepancy was primarily attributed to significant variations in emission factors for the *residential sector*. Given that EDGAR is a global inventory, the emission factors used may not accurately reflect the specific conditions in Korea. Due to the limited availability of studies on PAH emission factors in Korea, it was necessary to rely on emission factors from studies conducted in more advanced countries.

However, to enhance the accuracy of the PAHs emission inventory, empirical surveys and measurement-based studies are necessary to develop emission factors that better reflect Korea's actual emission characteristics. Based on these efforts, it is essential to continuously update the inventory. Accordingly, if locally appropriate emission factors that consider regional characteristics and technological levels are developed in the future, they can be incorporated to further improve and refine the inventory. On the other hand, for Speciation Profile-Based approaches such as the use of GP and PP coefficients derived from MOVES, it is important to note that the emission characteristics may significantly vary depending on engine types and the adoption of emission control technologies. These detailed variations are difficult to fully account for using generalized ratios developed in other countries. Thus, future research should focus on developing Korea-specific speciation profiles that better capture the emission characteristics of domestic vehicles and fuels.

In addition, uncertainty analysis of PAHs emissions was conducted using error propagation equations, resulting in an estimated overall uncertainty range of ±103.8 %. This level of uncertainty is expected to decrease in the future as more reliable activity data and emission factors become available.

The inventory developed in this study has enhanced the understanding of the emission status of PAHs in Korea. Emission sources that were previously overlooked in earlier research were incorporated, enabling detailed estimation of emission quantities at the province/local level. In contrast to prior studies that only presented the total emissions of 16 PAHs, this study allowed for the calculation of emissions for each of the 16 PAH compounds individually. Given the limited research on PAH emission inventories in Korea, this study holds significant academic and policy importance as it is the first to propose a foundational methodology for inventory development. Consequently, the primary contribution of this research lies in establishing a comprehensive methodology applicable across various years and emission sources. Based on this framework, continuous updates to activity data and emission factors will facilitate ongoing improvements to the inventory, providing a crucial basis for formulating effective PAH emission reduction strategies in Korea. However limitations in collecting emission factors prevented the inclusion of sources such as *fugitive dust* and *agricultural Sector*, which are not related to combustion activities. While emissions from these unconsidered sources may be relatively small, they do contribute to PAHs emissions. Therefore, it is essential to include them in future studies to ensure comprehensive emission calculations.

CRediT authorship contribution statement

Min-Young Choi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Jinseok Kim:** Methodology, Conceptualization. **Hyejung Hu:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Jiyi Lee:** Validation. **Ahn Lee:** Methodology. **Jaeyoon Lee:** Validation, Formal analysis. **Younha Kim:** Validation, Formal analysis. **Jung-Hun Woo:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Min-Young Choi reports financial support and article publishing charges were provided by Korea Environmental Industry and Technology Institute. Jung-Hun Woo reports financial support was provided by Korea Environmental Industry and Technology Institute. Jinseok Kim reports financial support was provided by Korea Environmental Industry and Technology Institute. HyeJung Hu reports financial support was provided by Korea Environmental Industry and Technology Institute. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2025.121692.

Data availability

Data will be made available on request.

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